THE PITOT TUBE AS A STEAM METER

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INDEX.

It is the purpose of this thesis to study two applications of the pitot tube as a steam meter, and to determine as far as possible, the practicability of using these devices as such.

The first of these applications of the pitot tube is shown in Fig. 1, and for convenience will be known as an impulse meter. Two holes are tapped in the steam pipe through which the steam is flowing, one for the pitot tube D, and the other for the static tube S. The latter tube admits the static pressure of the steam into the meter, and provides the means for returning any condensation that may gather in it. The stream of steam entering the meter through the pitot tube is projected through the nozzle M against an aluminum disc A, mounted on needle bearings. The disc has a broad smooth edge, so as to give as great a turning effort from the jet as possible. A spiral spring G is attached to the disc and to the body of the meter, providing an accumulative resistance which the jet must act against. A bar magnet N is also attached to the disc. On the outside of the meter

is mounted a second bar magnet, to which is attached a pointer, so that any movement of the disc will be indicated outwardly by this pointer. This meter was tested for the purpose of determining what the relation would be between the amount of steam flowing and the deflection of the needle.

Fig. 2 gives diagrammatically the arrangement of the piping used in conducting the tests. The steam first passed through the separator S to the drop leg B, at the bottom of which was a drip D. The globe valve V_1 was used for keeping the pressure constant in the part of the system following it. There was also a drip at the bottom of the riser C, both this and the drip D being kept slightly open at all times during the tests. The meter was attached to the pipe P as indicated in the figure, this pipe being a 3-inch extra heavy with an internal diameter of 2.893 square inches. The calorimeter and pressure gauge were fitted to the pipe just above the meter, the former being of the throttling type, and the latter a Crosby Test Gauge, #500989. At the further end of the system was

located a second globe valve V, this being used to vary the velocity of the steam. From this valve, the steam passed into a Wheeler surface condenser, from which it was discharged into suitable weighing tanks.

The method of conducting a test was as follows. Steam was gradually admitted, first to the drop leg B, and then through the valve V_1 into the rest of the sytstem. The drips were opened so as to drain all condensation, and the system was allowed to stand this way until thoroughly warmed up. After thus heating the pipes, the condenser pump was started, and the valve V opened, allowing steam to pass into the condenser. By manipulating the two valves V and V_1, any desired pressure and rate of flow could be obtained, within the capacity of the apparatus. Readings were taken every five minutes of the meter and calorimeter temperature, the pressure being closely watched and kept constant as before described. The weight of steam passing through the pipe was taken once for the entire run.

The first test was made at the maximum capacity of the apparatus, this being limited by a relief valve at the entrance to the condenser, which opened to the atmosphere when the velocity became too great. The low limit given by this valve was due to the fact that the steam entered the condenser through a 2-inch pipe, after passing through the three inch pipe, thus increasing the velocity greatly at this point.

The dial of the meter was divided into 100 parts, and it was found that the maximum capacity of the system gave a deflection of less than half a revolution of the needle. This meant that an enormous amount of steam was passing, as compared with the deflection, being very nearly 4000 pounds an hour. The velocity of the steam was thus a little over 9000 feet a minute. Furthermore, the friction of the bearings was so great as compared with the turning effort exerted by the steam, that considerable jarring of the meter was necessary in order to make it assume its proper reading. The data taken during the tests on this meter is given

on plates 1, 2, and 3, and is plotted on plate 4.

From plate 4 it will be seen that the be havior of the meter was very erratic. In the 50-pound series of tests, a reading of 3.37 on the dial gave a smaller weight of steam than a reading of 2.76. Again, in the 60-pound series, a reading of 1.88 gave less steam than a reading of 1.13. A consideration of the points as plotted, however, would indicate that there is very probably some law which holds between the meter reading and the weight of steam passing, as they follow, very roughly it is true, a general curve. From the behavior of the pointer with regard to assuming a position, as before described, the conclusion follows that in the meter under test, the friction of the bearings was too great to give dependable readings. An instrument of much finer construction, having jeweled bearings, and provisions for preventing any warping due to the internal pressure of the steam, would permit of a more accurate investigation of this type of meter, and would probably disclose a definite relationship, as before mentioned.

Further tests on the impulse meter being deemed inadvisable because of its inaccuracy, attention was turned to the second form of meter. This is shown in section in Fig. 3, and will be known as a gauge glass meter, since its readings are taken from the gauge glass. As in the case of the impulse meter, two tubes are necessary, the pitot and the static, and in addition, a third connection G is made to the steam pipe. The condensation which takes place in the static tube S is drained into the chamber N through the tube F. The chamber N can become filled only to the level of the top of the tube P, any surplus condensation being returned by it to the steam pipe through the water seal U and the pipe G. The upper end of P is fitted with a corrugated ferrule which reduces the effect of capillarity to a negligible quantity. The pressure exerted by the steam entering the pitot tube is transmitted to the surface of the water in the chamber N, forcing part of it into the gauge glass W the upper end of which is connected to the static tube S. The pitot tube connection to the chamber

N is made directly over the discharge tube P. This permits all condensation that may take place in the pitot tube to drain directly into the discharge, thus providing a dry pitot tube. The head H given by the column of water in the gauge glass should then be the true head due to the velocity, provided that there is no aspiration at the end of the static tube S. Prof. Gebhardt states (Jour. A. S. M. E., Nov. 1909) that there is no appreciable aspiration effect with velocities under 6000 feet per minute, and as these tests are all for low velocities of flow, it will be assumed that there is no aspiration The theory of the pitot tube which follows, was taken from Prof. Gebhardt's paper on steam meters (Jour. A. S. M. E., Nov. 1909). Other meters of the same general type as the one under discussion have given values of the coefficient c, which enters the equation, of unity. These meters had a number of defects which have been remedied in the later form of instrument, but as will be mentioned further on, the theoretical calculations will be made with c equal to unity.

The theoretical determination of the weight of steam flowing through a pipe by means of the pitot tube is arrived at from its well known formula,

$$v = c\sqrt{2gH}. \tag{1}$$

Since the end of the pitot tube is placed in the center of the pipe where the velocity of the steam is a maximum, the v of the above equation must represent the maximum velocity. The other terms of the equation are:

c = an experimental coefficient

g = acceleration of gravity

H = height of a column of steam equal in weight to the water column of the meter.

To get the value of H in terms of known quantities, let

d_w = weight of one cubic foot of water in the gauge glass of the meter

d_s = weight of one cubic foot of steam passing through the pipe.

h = height of water in the gauge glass in inches.

Then

$$H = \frac{h}{12} x \frac{d_w}{d_s}$$

Equation (1) then becomes

$$v = 2.316\sqrt{\frac{d_w}{d_s} h} \qquad (2)$$

Now let

w = weight of steam flowing in pounds per hour

a = area of section of pipe in square inches

r = ratio of the mean to the maximum velocity.

Then the actual weight of steam flowing per hour will be given by

$$w = 3600 x 2.316 c\sqrt{\frac{d_w}{d_s} h} \ x \ r \ x \frac{a}{144} \ x \ d_s$$

$$= 57.9 car\sqrt{d_w d_s h} \qquad (3)$$

For a 3-inch extra heavy pipe of the kind that was used for these tests, it has been found that the ratio r is equal to .82. Furthermore, in meters of the same general type as the one now under discussion, it has been found that the coefficient c is unity. For this reason, c will be assumed as unity in this equation. The internal diameter of

the pipe is 2.892 inches, giving an area of 6.569 square inches. Substituting the above values of c, a, and r in equation (3), we have

$$w = 57.9 \times .82 \times 6.569 \times 1\sqrt{d_w d_s h}$$
$$= 312\sqrt{d_w d_s h}.$$

The temperature of the water in the gauge glass of the meter was on the average very close to the normal atmospheric boiling point of water, so that the density of this water was taken as 60 pounds per cubic foot. For the conditions under which the 30 pound(gauge) tests were made, the formula becomes

$$w = 783\sqrt{h}$$ Abs. press. 44.43# d_s .1052#

For the 40 pound tests, the formula becomes

$$w = 861\sqrt{h}$$ Abs. press. 54.58# d_s .1277#

For the 50 pounds tests, the formula becomes

$$w = 933\sqrt{h}$$ Abs. press. 64.53# d_s .1494#

For the 60 pound tests, the formula becomes

$$w = 998\sqrt{h}$$ Abs. press. 74.50# d_s .1711#

The density of the steam in each case was taken from Peabody's Steam Tables. From the above formulae, the theoretical flow was calculated for each reading taken on the meter.

The method of conducting the tests on this meter was exactly the same as that described for conducting the tests on the impulse meter. The gauge glass of the meter was surrounded by a slotted sleeve, the edge of which was graduated to tenths of an inch. The zero reading of the meter was determined for each series of tests by closing the velocity regulating valve entirely, and allowing the water column to come to rest very gradually. In every instance, the zero reading was found to be at .58 inches on the sleeve. Preliminary runs showed that the variations were very small at constant pressures, so that 20-minute runs were considered long enough.

Plates 5 to 12, inclusive, contain the running logs of the tests conducted. The average results, together with the calculated results are given on plates 13 and 14. On plates 15 to 18, will be found the curves, both theoretical and actual, plotted from the data given on the average result plates. In each case, the curve for the actual performance of the meter was placed under

the theoretical curve for that pressure. It is immediately apparent that the assumption of the value of c equal to unity is not correct. The ratio of the actual to the calculated flow is given with the average results, and is the proper value of c. This ratio varies considerably at low velocities. For mean velocities of over 3000 feet per minute, however, the ratio becomes fairly constant. The average value of the constant is .8 for velocities above 3000 feet per minute, the greatest deviation from this being about 2 per cent. This, then, is the proper constant for the meter tested.

In view of the fact that other tests have indicated that the constant should be unity, it may be well to discuss the possibility of a defect in the instrument. A ten inch column of water corresponds to a pressure of about .35 pounds per square inch. This means that the difference in pressure between the static and pitot tubes when supporting a column of water of this length is but .35 pounds. It is evident that a leak in either tube, however slight it may be, will cause a very

large variatien in the height of the water column. The instrument was very carefully examined, however, and no defects of any kind were found, so that the probability of a keak was very small.

As an indicating instrument, this arrangement gives satisfactory results. The tests demonstrate that there is a definite relation existing between the flow of the steam and the indications of the meter, and the variation of the actual from the theoretical results, using the constant as here determined, should not be over three per cent at the most. The fact that it cannot be made recording, precludes the possibility of using the instrument commercially.

The gauge used for indicating the steam pressure was calibrated at the end of each day's running for the pressures at which it had been used. The calibration was performed with a Crosby gauge tester, and in every case, it was found that the gauge was correct, necessitating no calibration curve. A certified thermometer was not available for comparison with the calorimeter

thermometer, but its boiling point was found to be correct within a fraction of a degree. It was also compared with a thermometer whose bore was known tob be uniform, and the rise of the mercury columns was found to be equal through the range at which it had been used. It was therefore assumed that the thermometer was correct, this asumption being reasonable under these conditions.

PLATES.

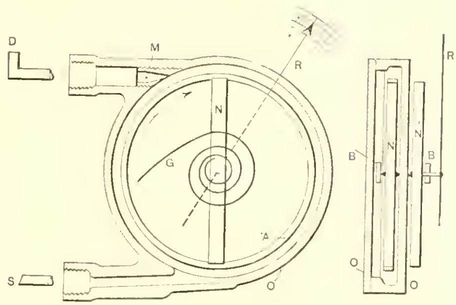


Fig. 1.

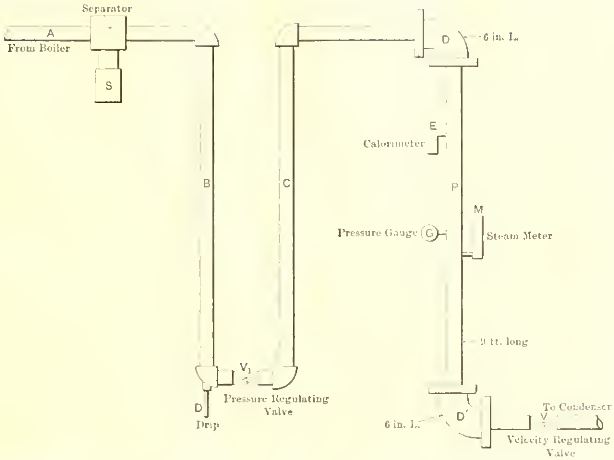

Separator
A
From Boiler
S
B
C
V1
D
Drip
Pressure Regulating Valve
D
6 in. L.
E
Calorimeter
P
M
Pressure Gauge
G
Steam Meter
9 ft. long
6 in. L.
D'
To Condenser
V
Velocity Regulating Valve

Fig. 2.

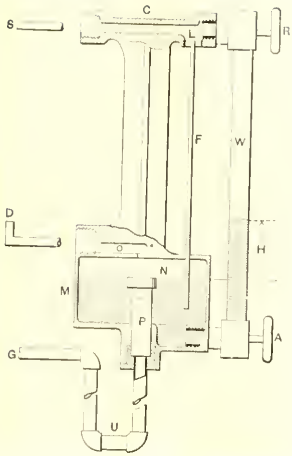


Fig. 3.

Running Log.

Diam. Pipe 2.892" Barometer 28.80"

Press.	Meter	Calorimeter	Tare Wt.	Final Wt.	Net Wt.
50#	4.71	261.5°	534	1592	1058
"	4.72	260.5			
"	4.74	260.5			
"	4.74	261			
"	4.78	261.5	539	1396	857
"	4.76	261			
"	4.82	261.5			
Average	4.75	261			1915
50#	3.80	262	539	1421	882
"	3.80	262			
"	3.78	262.5			
"	3.78	263			
"	3.76	263	534	1188	654
"	3.77	262			
"	3.77	263			
Average	3.78	262.5			1536
50#	3.35	264	533	1335	802
"	3.32	263.5			
"	3.38	263			
"	3.39	263			
"	3.34	264	541	1180	639
"	3.42	264			
"	3.42	264.5			
Average	3.37	263.7			1441
50#	2.70	264	539	1683	1144
"	2.73	264			
"	2.70	259			
"	2.78	258			
"	2.70	257	531	918	387
"	2.80	258			
"	2.90	258			
Average	2.76	259.7			1531

Duration of runs, — 30 minutes.

Running Log.

Diam. Pipe 2.892" Barometer 29.40"

Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net Wt.
60#	3.80	264°	532	1409	877
"	4.30	262			
"	3.50	261			
"	3.50	262			
"	3.80	262	540	1360	820
"	3.80	263			
"	4.10	263			
Average	3.83	262.4			1697
60#	3.00	263	538	1431	893
"	2.50	263			
"	2.78	264			
"	2.58	264			
"	2.64	267	534	1242	708
"	3.50	268			
"	3.40	268			
Average	2.91	265.3			1601
60#	2.65	265	533	1317	784
"	2.58	265			
"	2.56	265			
"	2.70	265			
"	2.67	265	540	1167	627
"	2.76	266			
"	2.78	262			
Average.	2.67	264.7			1411

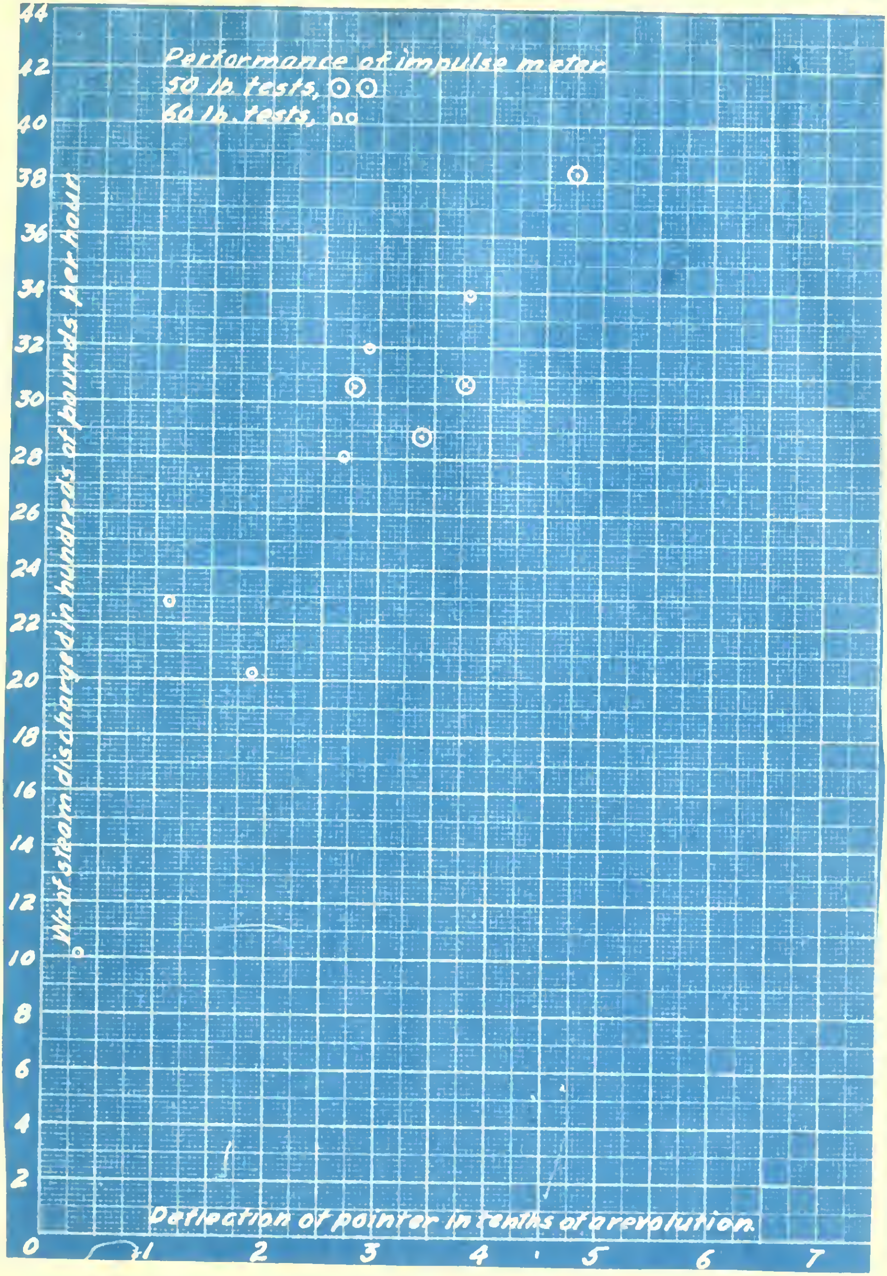
Duration of runs, - 30 minutes.

Running Log.

Diam. Pipe, 2.892". Barometer 29.40"

Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net Wt.
60#	2.40	260°	540		
"	2.00	262			
"	1.80	261			
"	2.00	263			
"	1.50	263			
"	1.60	262			
"	1.80	262		1558	
Average	1.88	261.8			1018
60#	1.26	261	577		
"	1.25	261			
"	1.12	260.5			
"	1.10	263			
"	1.30	264			
"	1.00	264			
"	.90	265		1720	
Average	1.13	262.6			1143
60#	.40	262.5	553		
"	.25	262			
"	.42	260.5			
"	.25	260.5		1061	
"					
"		15 minute run.			
"					
Average	.33	261.4			508

Duration of runs, - 30 minutes.



Performance of impulse meter.
50 lb. tests,
60 lb. tests,
Wt. of steam discharged in hundreds of pounds per hour
Deflection of pointer in tenths of a revolution.
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
1
2
3
4
5
6
7

Running Log.

Diam. Pipe, 2.892".					Barometer, 29.40"
Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net. Wt.
30#	.90"	242°	531		
"	.88	241			
"	.92	240.5			
"	.86	240			
"	.90	239.5		611	
Average	.89	240.6			80
30#	1.93	240	611		
"	1.88	241.5			
"	1.90	242.5			
"	1.90	243			
"	1.88	243		842	
Average	1.90	242			231
30#	2.88	244	532		
"	2.85	245			
"	2.82	244			
"	2.85	244.5			
"	2.86	245.5		846	
Average	2.80	244.6			314
30#	3.85	247	846		
"	3.92	247			
"	3.80	245			
"	3.86	245			
"	3.90	244.5		1227	
Average	3.87	245.7			381

Duration of runs,—20 minutes.

Running Log.

Diam. Pipe, 2.892". Barometer 29.40"

Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net Wt.
30#	5.05"	244°	532		
"	5.08	244			
"	5.05	246			
"	5.02	248			
"	5.00	248		983	
Average	5.04	246			451
30#	6.10	248	983		
"	6.13	245			
"	6.18	244			
"	6.08	245			
"	6.15	246		1481	
Average	6.13	244.4			498
30#	7.21	247	531		
"	7.21	248			
"	7.29	247			
"	7.25	245			
"	7.25	245		1081	
Average	7.24	246.4			550

Duration of runs, – 20 minutes.

Running Log.

Diam. Pipe, 2.892".			Barometer 29.70"		
Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net. Wt.
40#	.95"	246°	528		
"	.95	249			
"	.98	249.5			
"	.97	250			
"	.96	250		631	
Average	.96	248.9			103
40#	1.70	248	825		
"	1.82	249			
"	1.65	248			
"	1.72	249			
"	1.70	249		1049	
Average	1.72	248.6			224
40#	2.82	254.5	546		
"	2.78	254			
"	2.82	254			
"	2.78	254			
"	2.82	253		874	
Average	2.80	253.9			328
40#	3.80	253	531		
"	3.75	251			
"	3.72	251			
"	3.76	249.5			
"	3.70	249.5		945	
Average	3.74	250.8			414

Duration of runs, — 20 minutes.

Running Log.

Diam. Pipe, 2.892". Barometer 29.70"

Press.	Meter.	Calorimeter.	Tare Wt.	Final Wt.	Net Wt.
40#	5.03"	250°	542		
"	5.00	251			
"	4.95	252			
"	4.98	251			
"	4.95	250		1021	
Average	4.98	250.8			479
40#	6.00	251	528		
"	5.98	252			
"	5.95	253			
"	5.95	253			
"	5.96	253		1074	
Average	5.97	252.4			546
40#	7.28	251	531		
"	7.25	252.5			
"	7.28	253.5			
"	7.28	252.5			
"	7.23	252.5		1131	
Average	7.26	252.4			600

Duration of runs, - 20 minutes.

Running Log.

Diam. Pipe 2.892". Barometer 29.60"

Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net Wt.
50#	1.00"	255°	631		
"	1.02	254			
"	1.00	254			
"	1.02	256			
"	1.01	255		754	
Average	1.01	254.8			123
50#	2.05	260	527		
"	2.05	260			
"	2.08	260			
"	2.05	260			
"	2.05	260		790	
Average	2.06	260			263
50#	3.05	258	790		
"	2.98	259			
"	3.00	258			
"	3.03	259			
"	3.00	259		1154	
Average	3.01	258.6			364
50#	3.98	259	1154		
"	3.95	258			
"	3.92	258			
"	3.95	257			
"	3.95	258		1623	
Average	3.95	258			469

Duration of runs, - 20 minutes.

Running Log.

Diam. Pipe, 2.892". Barometer 29.60"

Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net Wt.
50#	4.95"	256°	542		
"	4.95	257			
"	4.95	257			
"	4.95	257			
"	4.95	259		1060	
Average	4.95	257.2			518
50#	6.07	261	1060		
"	6.03	261			
"	6.05	259			
"	6.03	257			
"	6.08	256		1636	
Average	6.05	258.8			570
50#	7.00	256	542		
"	6.98	257			
"	6.92	258			
"	7.05	258			
"	6.98	258		1177	
Average	6.99	257.8			635

Duration of runs, - 20 minutes.

Running Log.

Diam. Pipe. 2.892".			Barometer 29.54"		
Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net. Wt.
60#	1.48"	257°	553		
"	1.50	258			
"	1.50	258			
"	1.50	258			
"	1.50	258		808	
Average	1.50	257.8			255
60#	2.16	258	808		
"	2.16	258			
"	2.15	258			
"	2.14	259			
"	2.11	261		1142	
Average	2.14	258.8			334
60#	3.36	263	1142		
"	3.34	263			
"	3.34	263			
"	3.34	260			
"	3.32	260		1582	
Average	3.34	261.8			440
60#	4.48	259	542		
"	4.50	259			
"	4.46	260			
"	4.48	262			
"	4.46	264		1096	
Average	4.47	260.8			554

Duration of runs, — 20 minutes.

Running Log.

Diam. Pipe 2.892". Barometer 29.54"

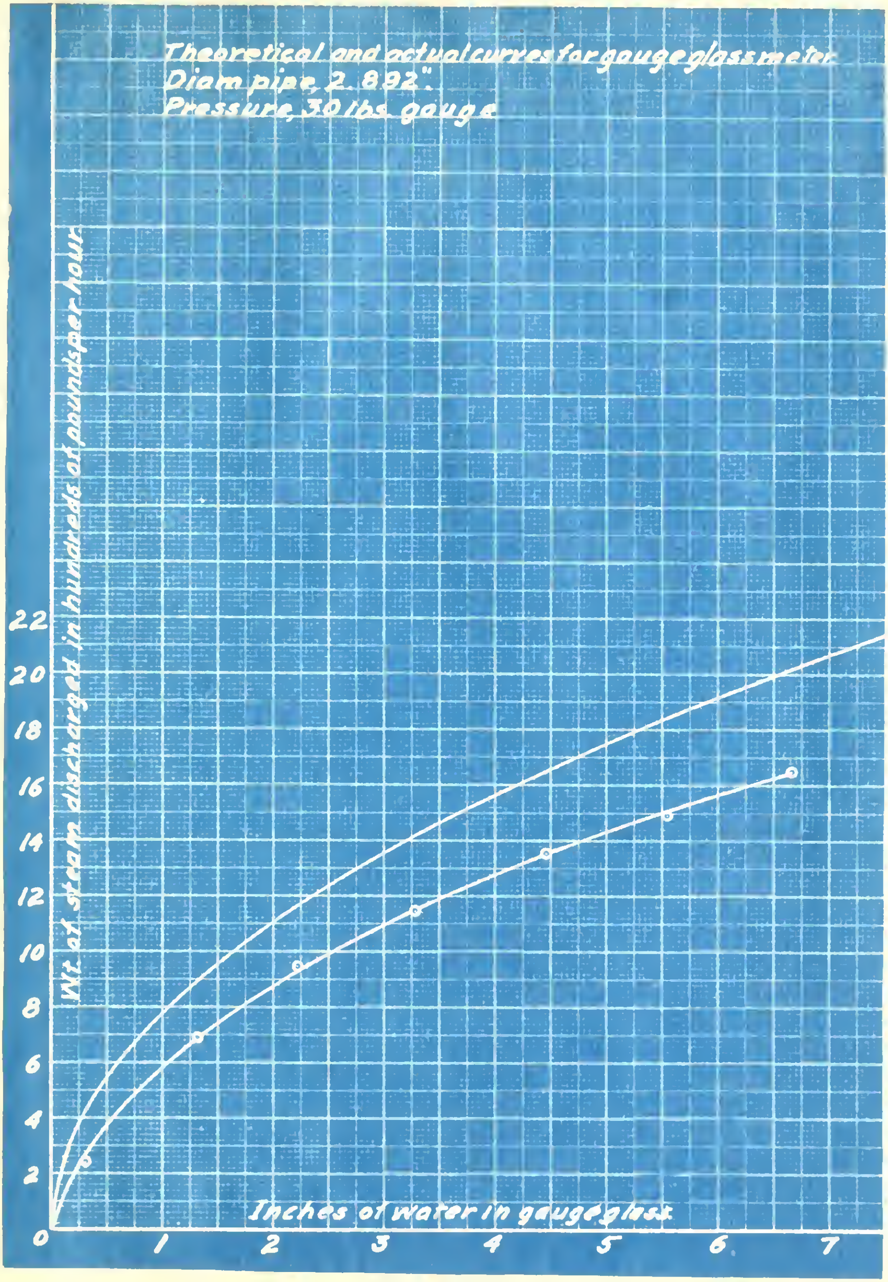
Press.	Meter.	Calorimeter	Tare Wt.	Final Wt.	Net Wt.
60#	5.42"	264°	543		
"	5.42	263			
"	5.42	263			
"	5.40	262			
"	5.40	261		1129	
Average	5.41	262.6			586
60#	6.24	260	545		
"	6.22	259			
"	6.20	259			
"	6.22	260			
"	6.22	260		1186	
Average	6.22	259.6			641
60#	7.35	261	545		
"	7.32	262			
"	7.33	262			
"	7.32	262			
"	7.32	263		1250	
Average	7.33	262			705

Duration of runs, -20 minutes.

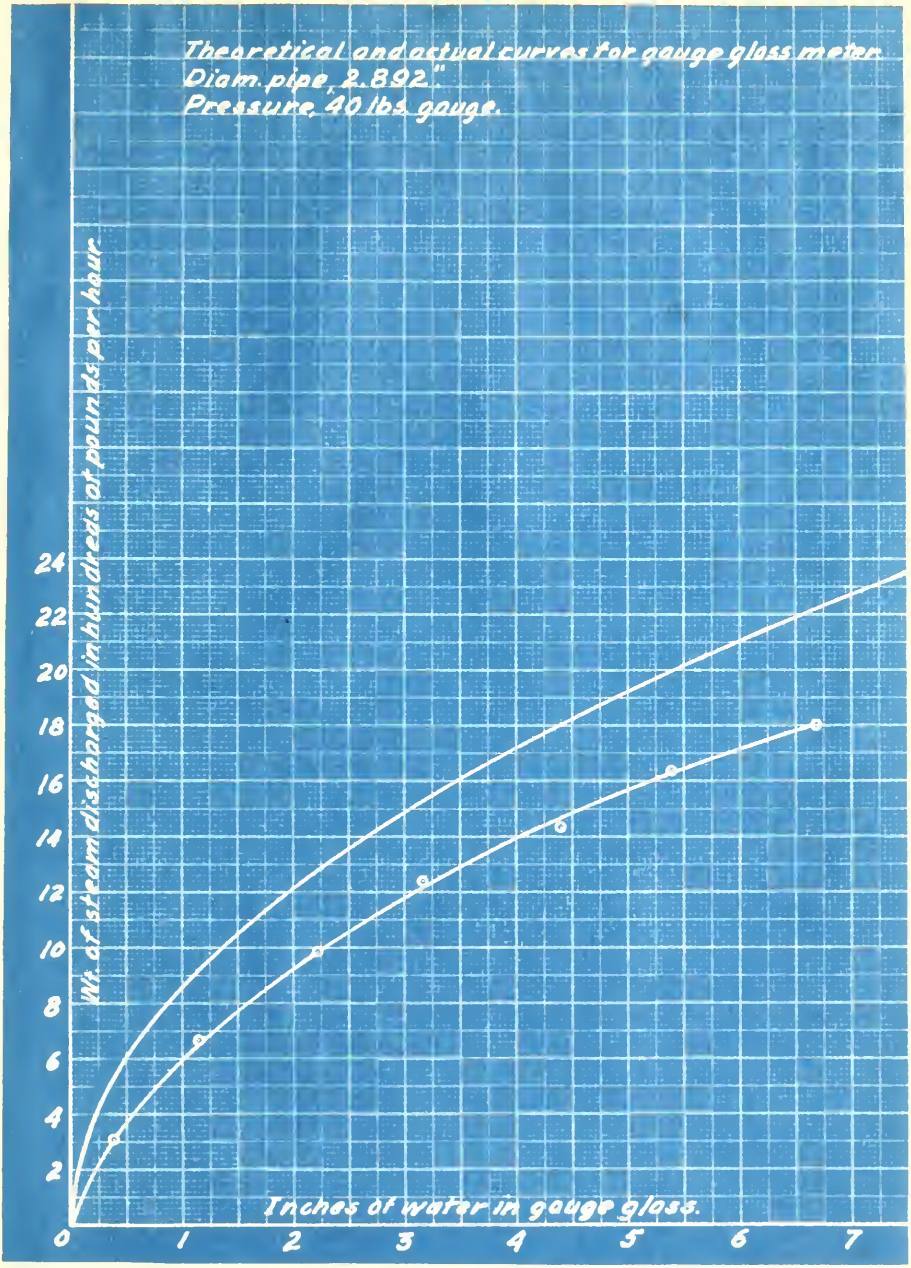
Average Results.								
Barometer, 29.40	Pressure, 30 lbs.		Diam. Pipe, 2.892"		Zero Reading, .58"			
Meter.	Meter Cor. (h)	$\sqrt{h}$	Wt. per hr.	Wt. per hr. Calculated	Ratio	Cal. Temp.	Quality x	Av. Vel. ft/min
.89	.31	.557	240	436	.551	240.6	99.7	830
1.90	1.32	1.149	693	900	.770	242	99.8	2396
2.80	2.22	1.490	942	1168	.806	244.6	99.9	3256
3.87	3.29	1.814	1143	1421	.804	245.7	99.9	3951
5.04	4.46	2.112	1353	1652	.816	246	100	4677
6.13	5.55	2.356	1494	1844	.809	244.4	100	5165
7.24	6.66	2.580	1650	2020	.815	246.4	99.9	5704
Barometer 29.70	Pressure 40 lbs.							
.96	.38	.676	309	532	.580	248.9	99.4	880
1.72	1.14	1.068	672	920	.730	248.6	99.4	1915
2.80	2.22	1.490	984	1283	.763	253.9	99.7	2804
3.74	3.16	1.778	1242	1531	.807	250.8	99.5	3537
4.98	4.40	2.090	1437	1808	.831	250.8	99.5	4095
5.97	5.39	2.322	1638	2000	.817	252.4	99.6	4668
7.26	6.68	2.584	1800	2225	.806	252.4	99.6	5130

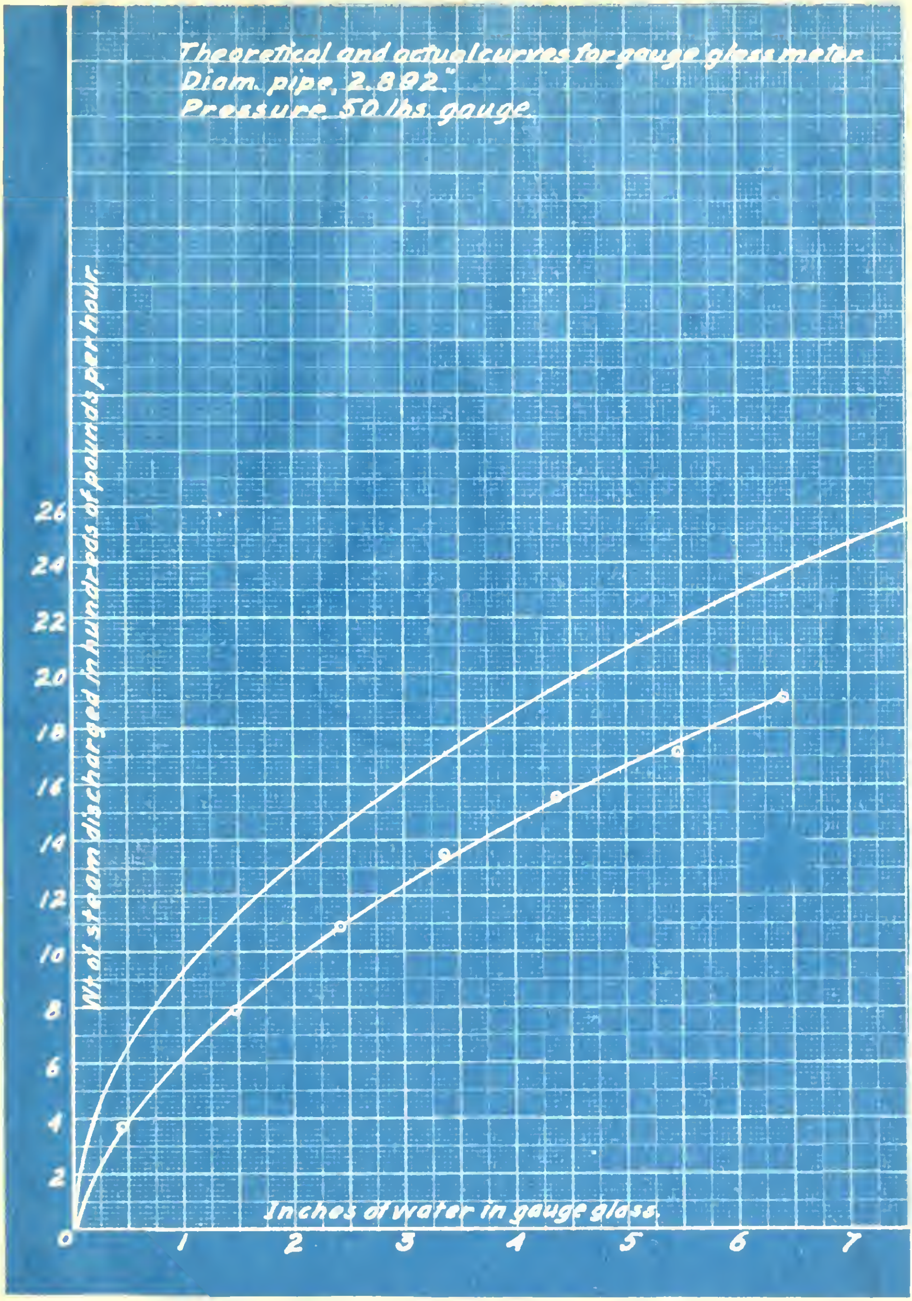
Average Results.

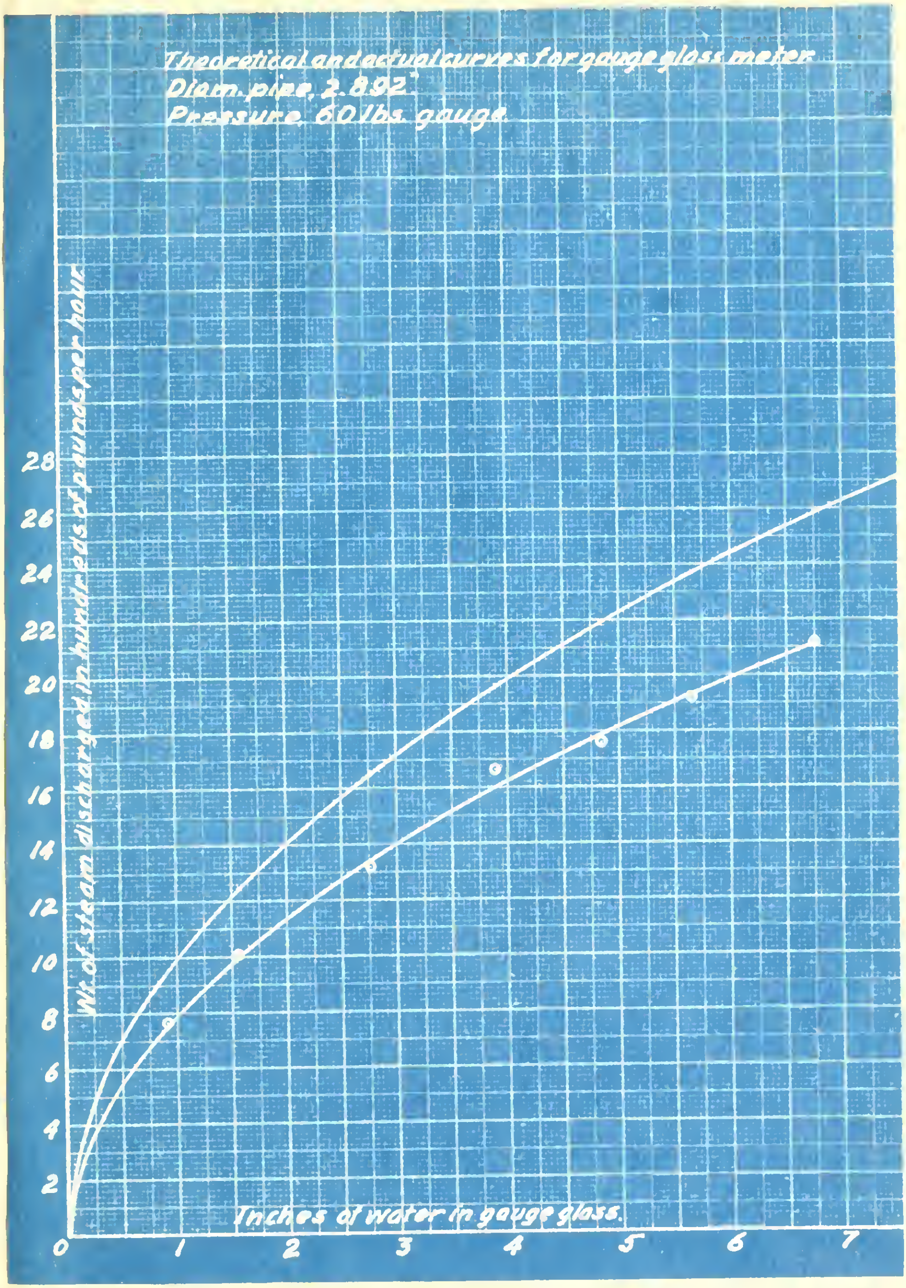
Meter.	Meter Cor. (h)	$\sqrt{h}$	Wt. per hr.	Wt. per hr. Calculated	Ratio.	Cal. Temp.	Quality x.	Av. Vel. ft./min.
Barometer 29.60	Pressure 50 lbs.	Diam. Pipe 2.892"	Zero Reading .58"					
1.01	.43	.656	369	612	.603	254.8	99.4	898
2.06	1.48	1.216	789	1135	.693	260	99.7	1921
3.01	2.43	1.559	1092	1456	.748	258.6	99.6	2659
3.95	3.37	1.836	1343	1713	.782	258	99.6	3270
4.95	4.37	2.090	1554	1950	.795	257.2	99.5	3784
6.05	5.47	2.339	1710	2182	.780	258.8	99.6	4164
6.99	6.41	2.532	1905	2363	.805	257.8	99.6	4638
Barometer 29.54	Pressure 60 lbs.							
1.50	.92	.959	765	958	.797	257.8	99.3	1626
2.14	1.56	1.249	1002	1248	.801	258.8	99.3	2130
3.34	2.76	1.661	1320	1660	.793	261.8	99.5	2806
4.47	3.89	1.972	1662	1970	.842	260.8	99.4	3535
5.41	4.83	2.198	1758	2195	.798	262.6	99.5	3737
6.22	5.64	2.375	1923	2372	.809	259.6	99.4	4088
7.33	6.75	2.598	2115	2595	.813	262.	99.5	4496



Theoretical and actual curves for gauge glass meter
Diam pipe, 2.892".
Pressure, 30 lbs gauge
Wt of steam discharged in hundreds of pounds per hour
22
20
18
16
14
12
10
8
6
4
2
0
Inches of water in gauge glass
1
2
3
4
5
6
7


Theoretical and actual curves for gauge glass meter.
Diam. pipe, 2.892"
Pressure, 40 lbs. gauge.
Wt. of steam discharged in hundreds of pounds per hour
24
22
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
Inches of water in gauge glass.


Theoretical and actual curves for gauge glass meter.
Diam. pipe, 2.882."
Pressure 50 lbs. gauge.
Wt. of steam discharged in hundreds of pounds per hour.
Inches of water in gauge glass.
0
2
4
6
8
10
12
14
16
18
20
22
24
26
1
2
3
4
5
6
7



Theoretical and actual curves for gauge glass meter
Diam. pipe, 2.892"
Pressure 60 lbs. gauge
Wt. of steam discharged in hundreds of pounds per hour
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
Inches of water in gauge glass.